Study on Determination of Fracture Toughness of Rocks with Core-based Specimens and Microstructural Characterization(コアを用いた岩石の破壊靱性評価と微視組織に関する研究)

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論　文　内　容　要　旨

Chapter 1　General Introduction

Rock fracture mechanics concept is being rapidly developed in many rock engineering fields such as energy production technology to develop natural resources including hydrofracturing for the optimun recovery of geothermal enerhgy, oil and gas, etc., because of its relatively simple fracture criteria in describing the failure of rock.

In fracture mechanics the failure criteria are based on fracture toughness or the critical value of fracture mechanics parameters which represent the crack resistance property of rock. The material property used in most experimental fracture mechanics studies is the plane strain fracture toughness K_{IC} which characterizes the magnitude of mode I (tensile mode) crack tip stress singularity when a crack starts to propagate in unstable manner. However the previous results on rocks were generally incomparable because the variety of specimen types and evalution methods were used and because these methods were usually modified from ASTM standard E-399 which is developed for metallic material.

The commission on Testing Method in ISRM (International Society for Rock Mechanics) proposed two standard-methods, chevron bend (CB) and short rod (SR), for determining the fracture toughness K_{IC} of rock materials in 1988. However this Suggested Methods do not describe the important criterion on the specimen size requirement to determine the specimen size independent fracture toughness. Moreover previous works have shown that the level II fracture toughness is not independent of specimen diameter according to rocks and that there exists a unique crack resistance curve where the corrected fracture toughness of rocks increases with crack extension until it reaches an almost constant value. Thus it is requisite to clarify the specimen size requirement to determine the inherent fracture toughness of rocks according to the Suggested Methods.

The increase of fracture toughness with the crack propagation is due to the formation of microcracks around a crack tip and non-linear region where portion of the crack is still interlocked. Accordingly the increase of fracture toughness with crack extension seems to have a close relation to rock microstructure. Furthermore it is well known that the microstructure of rock affects the material properties suck as fracture toughness, Young's modulus, etc. Therefore it has been very important to correlate the fracture propagation in rocks as well as the mechanical properties of rocks with rock microstructure by quantitative characterization of fracture propagation in rocks and rock microstructure through precise microscopic observation.

Chapter 2 Rock Fracture Mechanics and the ISRM Suggested Methods for Determining the Fracture Toughess of Rock.

In this chapter advantages and the problems associated with the Suggested Methods for determining the fracture toughness of rock were discussed. The methods use rock materials in the form of core specimens because rock is readily available in the form of core pieces and have two testing levels where level I testing assumes the linear elasticity while in level II testing the non-linearity correction is made with the degree of non-linearity to give the crack resistance of rocks. Method I uses a bend specimen with a notch cut perpendicular to the core axis. Method 2 uses a short rod specimen which has a notch cut paralel to the core axis. Thus anisotropy of fracture toughness can be evaluated. In both methods the ligament of the notched section has the form of a V or chevron.

Although the ISRM Suggested Methods have a number of advantages, they have an important problem to be solved. That is, the criterion for the size requirement to obtain the inherent fracture toughness of rocks has to be clarified.

Chapter 3 Fracture Toughness of Rocks Using the Standard Short Rod Specimen

The determination of the accurate fracture toughness of rocks is an essential prerequisite in many engineering fields. In this chapter in order to determine the fracture toughness of rocks from the view point of crack resistance curve, short rod testing based on the ISRM Suggested Methods was carried out for eight rocks in addition to the uniaxial tensile testing to determine the uniaxial tensile strength. The results of crack resistance curve for some rocks are shown in Fig. 1 as examples. From the results it is shown that the fracture toughness of most rocks increases with crack extension and those of four rocks reach an almost constant value at a certain crack extension Δa_c, which is called the critical crack extension in this study. This constant value can be regarded as the inherent fracture toughness K_{IC} of these rocks.

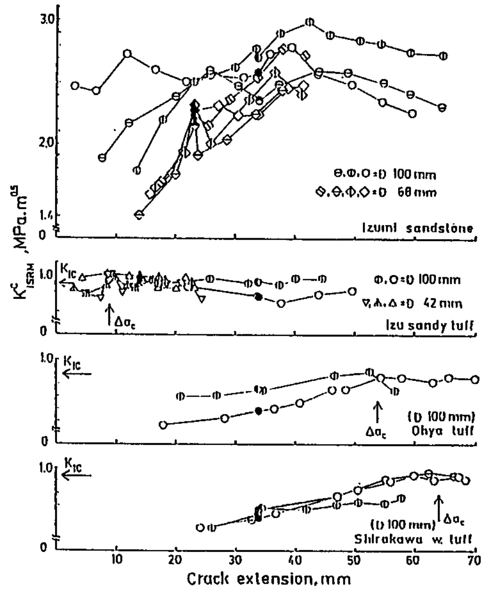

Fig. 1 Crack-resistance curve for some rocks.

Chapter 4 Specimen Size Requirement for Determining the Inherent Fracture Toughness of Rocks According to the ISRM Suggested Methods

It is well known that the specimen size will affect the evaluation of fracture foughness of rock. The criterion with respect to the specimen size is therefore required for examining the validity of the test. For the purpose the test results described in Chapter 3 together with those in the previous work were combined with the results from uniaxial tensile test to find the criterion for the necessary specimen size to determine the inherent fracture toughness of rock. In Fig. 2 the critical crack extension Δa_c is plotted against the characteristic length $(K_{IC}/\sigma_t)^2$ for seven rocks. From this figure, the following equation was determined with least squares method as the size requirement to determine the inherent fracture toughness of rocks:

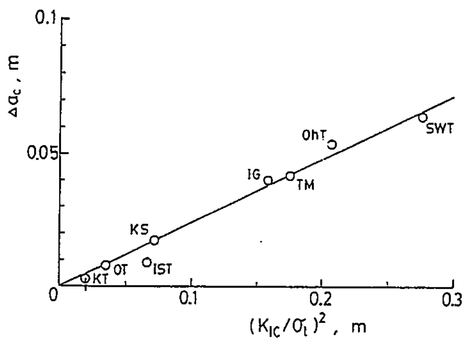

Fig. 2 The relation between Δa_c and $(K_{IC}/\sigma_c)^2$

$$\Delta a_c \geqq 0.24\,(K_{IC}/\sigma_t)^2 \qquad (1)$$

If it is written in the term of specimen diameter D, the size reqirement is given by the following equations:

for $SR: D \geqq 0.71 (K_{IC}/\sigma_t)^2$, (2)

for $CB: D \geqq 1.6 \ (K_{IC}/\sigma_t)^2$ (3)

Fig. 3 shows the relation between SR testing ($E_{i,SR}$). Since the relation is approximately linear, un known fracture toughness can be evaluated from this relation and consequently, once initial Young's modulus is determined with subsized specimen, the necessary specimen diameter to obtain size-independent fracture toughness can be roughly chosen by using quations (2) and (3) for the next trial.

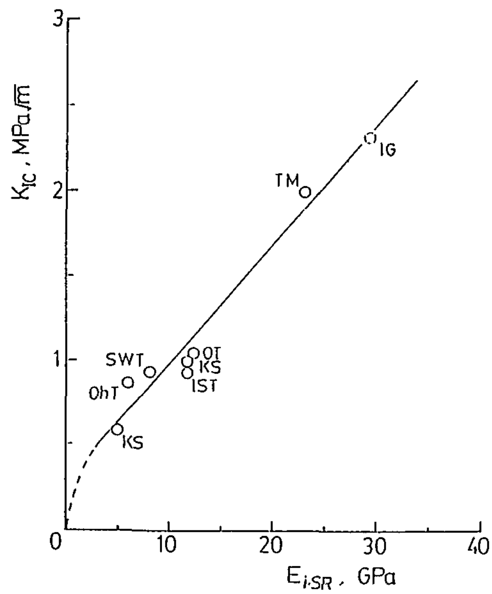

Fig. 3 The relation between K_{IC} $E_{i,SR}$

Chapter 5 Microscopic Observation of Mode I Fracture in Rocks and Its Significance in Fracture Toughness Evaluation

In this chapter it is aimed to investigate the relation berween the fracture propagation and microstructure of rocks. For the purpose rock microstructure was firstly quantitatively characterized by measuring the grain, etc. from the thin section which was cut parallel to the crack plane from the half of tested short rod specimens which were used in Chapter 3. Then another short rod fracture toughness testing based on the ISRM Suggested Methods was carried out for seven rocks to quantitatively characterize the fracture propagation and to clarity its relation to the rock microstructure.

The geometrical parameters such as area, perimeter, length and breadth of each grain and pore as well as the packing density and orientation of grain and pore were measured using a graphic tablet digitizer and a personal computer. Length and breadth were defined as the maximum and minimum Feret's diameter. The two-dimensional diameter of grain or pore obtained from the observation of thin section was deduced to three-dimensional diameter by using the Fullman's relation. The packing density of grain or pore area to the observed area.

To analyse the fracture propagation in rock, the paint was filled into a slot of notch during unloading immediately after the maximum load was reached in SR testing to dye the crack. The filled paint gave more clear view of crack propagation for measuring the crack length. Then the specimen was cut perpendicular to crack plane and along the core axis about in the center of specimen for microscopic observation.

Crack path is charaterized by the percentage of crack propagation modes and the waviness

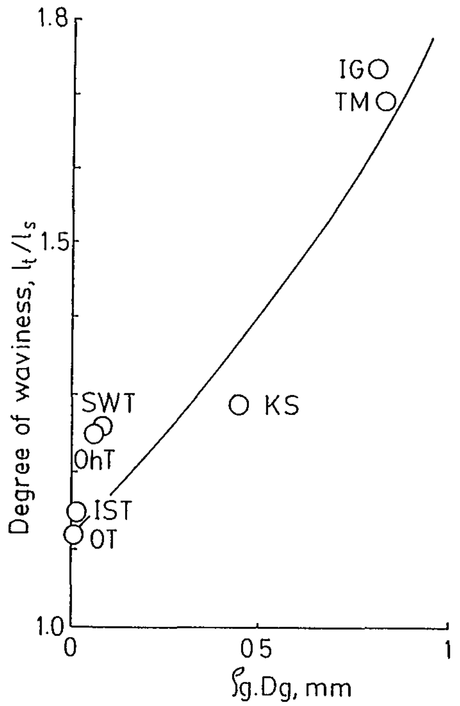

Fig. 4 The relation between ρg. Dg and the degree of waviness

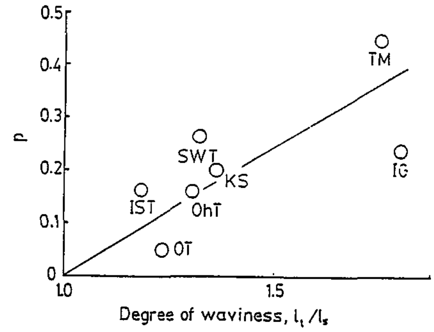

Fig. 5 The relation between the degree of waviness and p.

of crack path. The waviness of crack path was defined as the ratio of true crack length including crack branching to the straight length from the notch tip to the end of the crack.

The relation between the 3-D grain size Dg and the percentages of trans-and intergranular modes shows that the intergranular propagation is predominant and that the percentage of in tergranular mode decreases with Dg whereas the percentage of transgranular modes increases with Dg. Fig. 4 shows the relation between the combination of packing density ρg and Dg and the degree of waviness of the rocks. The waviness of crack propagation increases with both grain size and its packing density. The relation between the degree of waviness and the degree of non-linearity p is shown in Fig. 5. The degree of non-linearity p increases with the degree of wavines. Thus it can be said that both 3-D diameter and the packing density of grain increases the degree of waviness, which in turn increases the permanent displacement and therefore t he additional dissipated energy during the fracture growth.

Chapter 6 Quantitative Microstructural Characterization and Its Significance in the Inherent Fracture Propertes of Rocks.

In this chapter the rock microstructure was quantitatively analyzed by using both Howarth's texture coefficients and 3-D sizes of both grain and pore in order to correlate the rock microstructure with the critical crack extension and the mechanical properties of rocks such as fracture toughness K_{Ic}, initial Young's modulus and uniaxial tensile strength. The texture coefficient used in this study quatifies the geometrical relationships among both grains and pores as defined in following equation.

$$TC = \rho \left\{ \frac{No}{No+N1} \times \frac{1}{FFo} + \frac{N1}{No+N1} \times AR1 \times AF1 \right\}, \tag{4}$$

where ρ : packing density, No : number of grain or pore whose aspect ratio is smaller than 2, N1 : number of grain or pore whose aspect ratio is greater than 2, FFo : arithmetic mean of form factors which represent the degree of roughness along periphery, AR 1 : arithmetic mean of aspect ratios and AF 1 : angle factor which represents the degree of random orientation. The texture coefficient consists of two contributions. One is that from elongated shapes and the other that from relatively round shapes, which is distinguished by the aspect ratio of 2.

A quantitative microstructural coefficient (MC), which is a function of the combination of 3-D sizes and the texture coefficients of both grain and pore was proposed as in the following relation as a microstructural characteristic parameter to control the brittle fracture of rock:

$$MC = \frac{\exp(TCg \cdot Dg)}{\exp(TCp \cdot Dp)} \tag{5}$$

MC is plotted against fracture toughness in Fig. 6, which shows that there is an approximately linear relation between them. From the figure, the relations between MC and fracture toughness was determined by using the least squares method as in the following equation,

$$K_{Ic}\,(\mathrm{MPa}.\sqrt{\mathrm{m}}) = 0.313\,MC + 0.574. \tag{6}$$

Similarly, there are approximately linear relations between MC and initial Young's modulus and uniaxial tensile strength of rocks. Thus $TCg \cdot Dg$ increases the values of mechanical properties of rocks while $TCp \cdot Dp$ decreases them. Furthermore, once MC is determined from microscopic observation of thin section, K_{Ic} and uniaxial tensile strength can be estimated and consequently the necessary SR or CB specimen diameter to obtain size independent SR or CB specimen diameter to obtain size independent fracture toughness can be also roughly estimated by using equations (2) and (3).

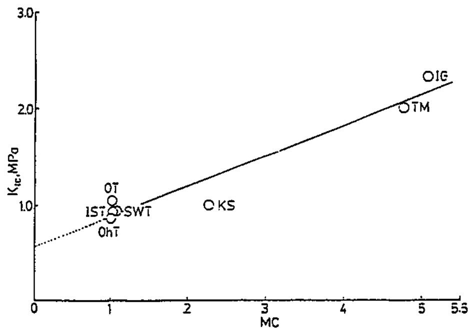

Fig. 6 The relation between fracture toughness K_{Ic} and microstructural coefficient MC.

The critical crack extension Δa_c was also correlated to the rock microstructure by the following equation.

$$\Delta a_c = kg \cdot TCg \cdot Dg + kp \cdot TCp \cdot Dp. \tag{7}$$

The constants kg and kp were 25.1 and 572, respectively. Conversely Δa_c of each rock was calculated from equation (7) by using the obtained values of kg and kp and the relation between Δa_c and the calculated Δa_c is plotted in Fig. 7, which demonstrates that equation (7) gives excellent estimation of Δa_c and that contrary to the mechanical properties, both TCg • Dg and TCp • Dp increases the required minimum length for the crack to grow in a steady state.

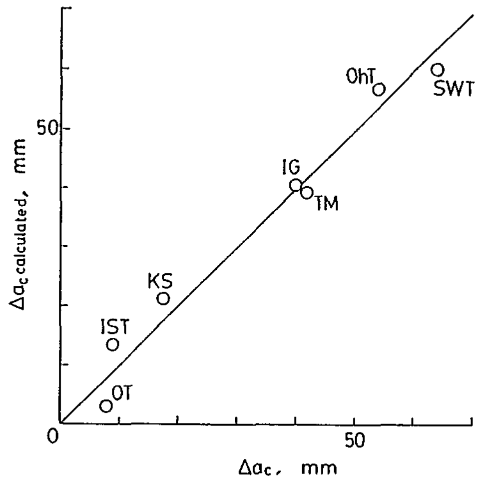

Fig. 7 The relation between Δa_c and Δa_c calculated.

Chapter 7 General Conclusion

This chapter summarizes main conclusions obtained in this study.

審 査 結 果 の 要 旨

岩石破壊力学は近年目ざましい発展をとげているが，この中で破壊靱性試験法は最も基礎となる計測技術である。最近，国際岩の力学会議で定めた岩石破壊靱性試験法はボーリングコアを利用するもので，工学的に注目されている重要な試験法であるが，完成した試験法でなく，今後解明されるべきいくつかの学術的課題が残されている。

本研究は，この学術的課題を取り上げ，コアを用いた岩石破壊靱性試験法の基礎を確立することを目的としており，さらに岩石の破壊靱性の微視組織依存性についても言及している。

第１章は序論で，本研究の背景と目的を述べている。

第２章は，国際岩の力学会議破壊靱性試験法の紹介である。

第３章では，鉱物組織及び微視組織の異なる８種類の岩石について，同一形状のショート・ロッド（SR）破壊靱性試験を実施した結果を述べている。本計測結果は岩石固有の破壊靱性評価のためにはき裂伝播曲線を用いるべきであるとの従来の提案を支持するもので，工学上重要なデータである。

第４章では，岩石の破壊靱性はき裂進展とともに増加するが，岩石固有のある進展量に達して飽和し，これが岩石固有値となるとの第３章の結果を用いて，試験片寸法に依存しない平面ひずみ破壊靱性（K_{IC}）の判別式を導いている。これは破壊靱性試験法を確立する上で最も重要な知見である。

第５章では，上記岩石すべてについて薄片顕微鏡観察を行ない，微視組織とき裂伝播経路の関係を検討している。特にき裂伝播経路に及ぼす結晶粒子径や空隙径の影響を論じた結果はこれまでにない新しい注目に値する結果である。

第６章では，第５章の観察結果をさらに発展させ，岩石を構成する結晶粒子，空隙及び母相の構成比率ならびにその組織（径・形態分布）を総合的に特徴化するための係数（微視組織形態評価係数）を提案している。この係数と破壊靱性，ヤング率及び引張強度などとの相関図はこれまでに無かった新しい破壊評価線図であり，極めて重要な知見である。

第７章は結論である。

以上要するに本論文は，鉱物組織及び微視組織の異なる岩石コア試験片の結果をもとに岩石の破壊靱性試験法の基礎を確立し，さらに岩石の破壊靱性とき裂伝播について，岩石組織による定量評価を試みたもので，資源工学，特に岩石破壊力学の発展に寄与するところが少なくない。

よって，本論文は工学博士の学位論文として合格と認める。